

GEOSCIENCE LASER ALTIMETER SYSTEM (GLAS) LOOP HEAT PIPES - AN EVENTFUL FIRST YEAR ON-ORBIT

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ABSTRACT

Goddard Space Flight Center's Geoscience Laser Altimeter System (GLAS) is the sole scientific instrument on the Ice, Cloud and land Elevation Satellite (ICESat) that was launched on January 12, 2003 from Vandenberg AFB. A thermal control architecture based on propylene Loop Heat Pipe technology was developed to provide selectable/stable temperature control for the lasers and other electronics over the widely varying mission environment.

Following a nominal LHP and instrument start-up, the mission was interrupted with the failure of the first laser after only 36 days of operation. During the 5-month failure investigation, the two GLAS LHPs and the electronics operated nominally, using heaters as a substitute for the laser heat load.

Just prior to resuming the mission, following a seasonal spacecraft yaw maneuver, one of the LHPs deprimed and created a thermal runaway condition that resulted in an emergency shutdown of the GLAS instrument.

This paper presents details of the LHP anomaly, the resulting investigation and recovery, along with on-orbit flight data during these critical events.

MISSION BACKGROUND

The principal mission of ICESat is to measure the surface elevation of the large ice sheets covering Antarctica and Greenland. Measurements of elevation-change over time will show whether the ice sheets are melting or growing as the Earth's climate undergoes natural and human-induced changes.

The Geoscience Laser Altimeter System (GLAS) instrument on ICESat (Figure 1) sends short pulses of green and infrared light through the sky 40 times a second, all over the globe, and collects the reflected laser light in a one-meter telescope. The elevation of the Earth's surface and the heights of clouds and aerosols in

the atmosphere are calculated from both precise measurements of the travel time of the laser pulses, and ancillary measurements of the satellite's orbit and instrument orientation. This marks the first time any satellite has made vertical measurements of the Earth through the use of an onboard light source.

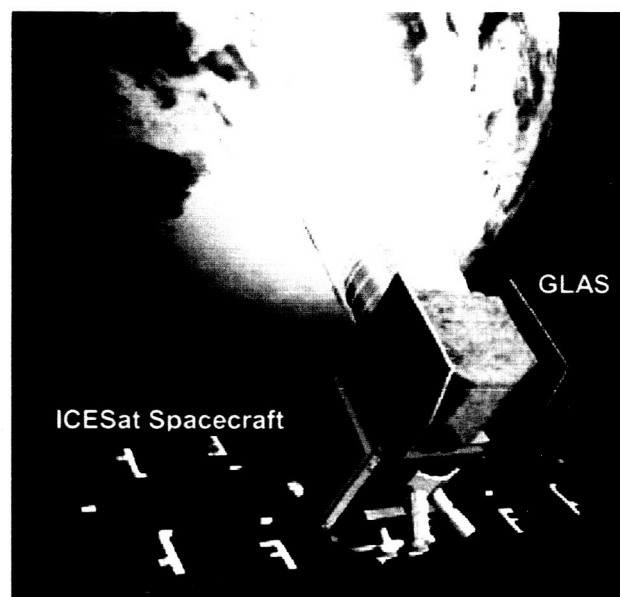


Figure 1 – Artist's rendition of ICESat [Credit: NASA]

Since ICESat's launch in January 2003, several hundred million laser shots¹ have been fired at the Earth (Figure 2). By measuring the precise time it takes for the laser pulses to bounce back to the satellite where the return photons are collected in a 1 m diameter telescope, GLAS can detect its distance from Earth's surface.

Combining this with knowledge of the exact location of ICESat in its orbit (to about one inch) obtained from the

¹ GLAS is a 2-channel laser altimetry and lidar science mission; an infrared pulse (1064 nm) is used for surface altimetry and cloud-top measurements, and a green pulse (532 nm) is used for measurements of thin clouds and aerosols.

Global Positioning System (GPS) along with onboard star camera (looking out the zenith side of GLAS) and gyroscopes to accurately locate the instrument position and laser pointing direction (within ~1.5 arc seconds), the height of the surface of Earth can be calculated (Figure 3).

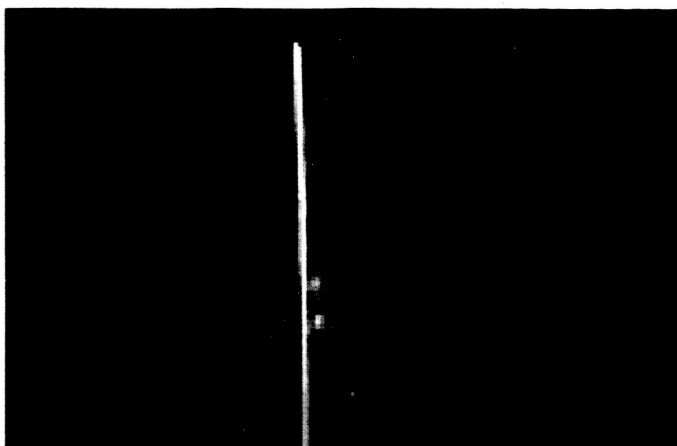


Figure 2 – GLAS Laser Pulse Seen From Earth

That information will be used to carefully calculate temporal changes in topography that will provide information about ice-sheet mass balance and will support predictions of cryospheric and sea-level responses to future climatic changes.



Figure 3 – GLAS Operation

GLAS THERMAL DESIGN OVERVIEW

The GLAS mission was the first NASA application of propylene LHP technology on a science instrument. The LHP was originally developed in the former Soviet Union. Dynatherm, through its parent organization DTX, transferred the Russian technology to the U.S. through a cooperative agreement with a Russian firm. The development approach undertaken by GSFC for the GLAS LHPs utilized engineering and prototype models to successfully demonstrate and validate the technology prior to implementation for flight [Baker, et al].

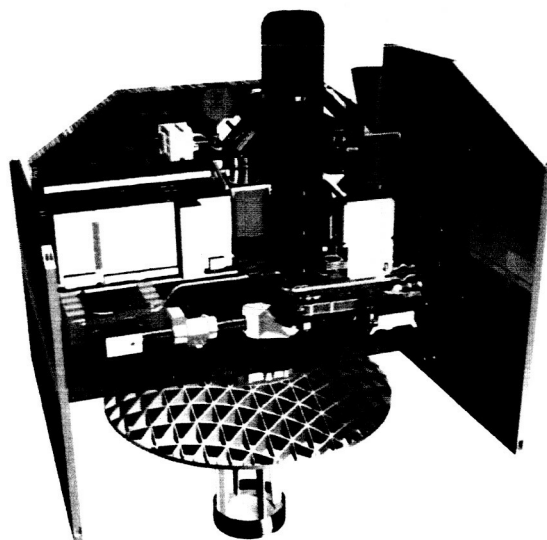


Figure 4 - GLAS Packaging (some structure and MLI removed for clarity)

Loop Heat Pipe (LHP) technology was utilized based on its high transport capability and the “variable” conductance necessary to maintain a constant evaporator temperature despite radiator temperature variations caused by the previously discussed environmental effects. GLAS uses two LHPs; one (LLHP) is dedicated to the three lasers, of which only one is on at any time, and the second (CLHP) controls the remaining dissipative components (gyroscope, star cameras, detectors, power supply/distribution and main electronics box). Propylene (C_3H_8) was selected as the working fluid based on its low freezing temperature. Electronic heater controllers with commandable setpoints are used to provide adjustable thermal control on-orbit to offset varying sun angles and BOL/EOL thermo-optical property degradation. Table 1 lists all operational and non-operational heater circuits. In the interest of brevity, only the LHP in-flight performance is discussed in this paper; all other thermal control features continue to perform nominally.

The GLAS design locates the optical and electronic components on two orthogonal composite optical benches (Figure 4 and Figure 5) that are mounted to the spacecraft with three titanium blade flexures to isolate GLAS from spacecraft induced distortion and jitter. To minimize thermal distortion of the optical benches, two complex traditional heat pipe networks were designed to collect the heat (330W) from the densely packaged sources, transport it to one of the two LHP evaporators, and ultimately reject it to space from the radiators. The complexity of these networks is seen in the “thermal-centric” LHP/heat pipe representation in Figure 6. Maintaining the various component temperatures within their respective allowable ranges was a function of the component location in the network and the numerous thermal interfaces between it and the LHP evaporators.

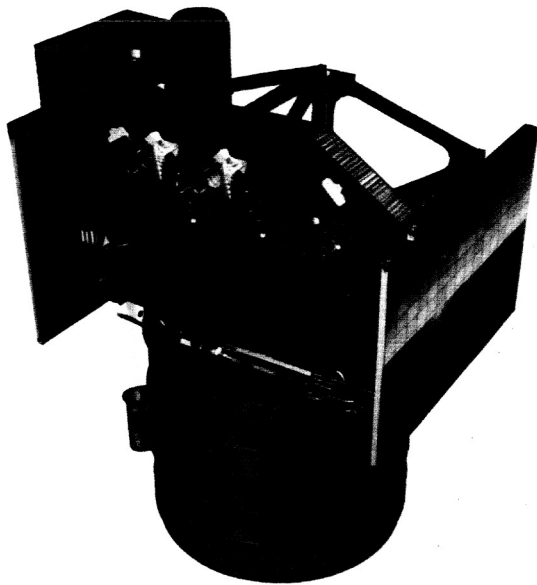


Figure 5 - Laser Transmit Path (LT1 firing)

A rigorous technology development and test verification program resulted in robust LHP performance during instrument and observatory thermal vacuum testing. Still, the flight units failed initial acceptance testing at GSFC; this was determined to be caused by insufficient compensation chamber (CC) volume, which created inadequate liquid levels in the compensation chambers to ensure the evaporator core was flooded in 1g during cold start-up conditions. A redesign of the CC resolved the fluid inventory issues and both flight units performed as expected throughout subsequent acceptance and flight instrument/observatory thermal vacuum testing.

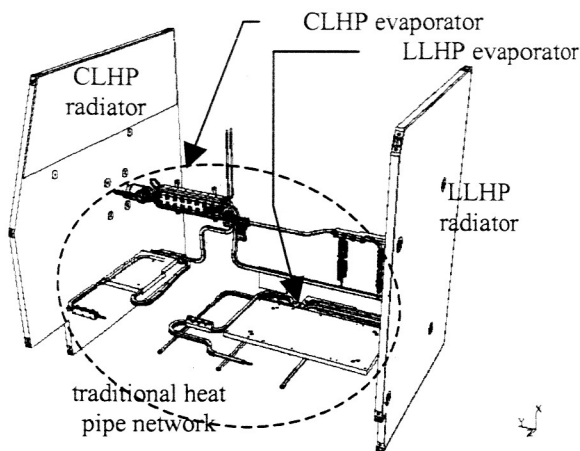


Figure 6 - GLAS Thermal Control Subsystem

Telemetry locations for the LHPs are shown in Figure 9 and Figure 10.

IN-FLIGHT THERMAL PERFORMANCE

Throughout the early mission operations, from post-launch through GLAS turn-on, the thermal control

subsystem performed nominally (Ref. 3), including start-up, set-point adjustment, and overall thermal balance as was expected from ground testing.

After activation on February 20th, 2003, Laser 1 performed initially as expected. However, on March 29th, it unexpectedly stopped pulsing after only 36 days of on-orbit operation. The effect on the Laser LHP at the time is seen in Figure 7. With the removal of the laser heat load, circulation slowed until the starter heater could be switched ON to maintain flow.

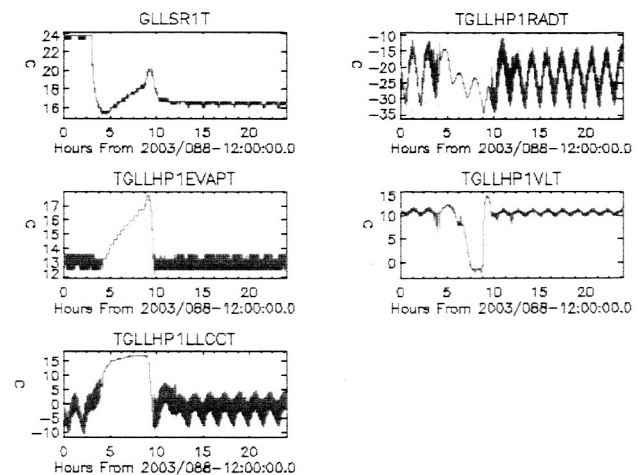
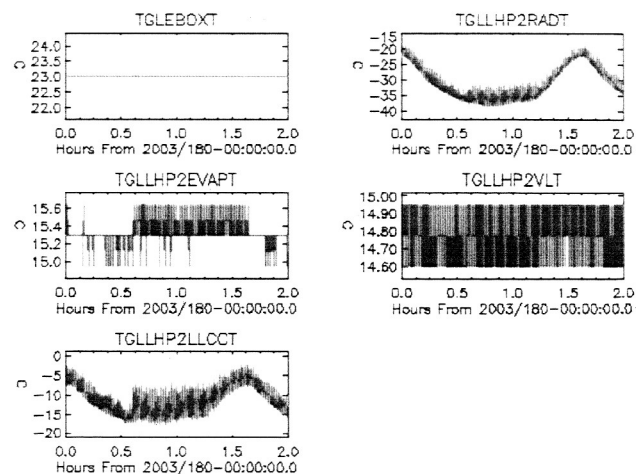
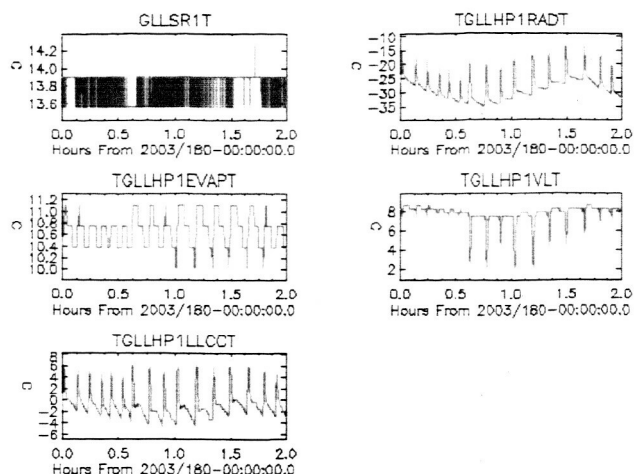


Figure 7 – LASER LHP (LHP1) at Laser 1 Failure

This heater remained on as a substitute heat load for the LLHP throughout the failure investigation. Sample temperature plots of the two LHPS during this investigation period are shown below.



Component LHP



Laser LHP

The ICESat Project appointed an Independent Goddard Anomaly Review Board (IGARB) on April 8, 2003 to investigate the laser failure.

The IGARB concluded that the most likely cause was an unexpected failure mechanism in a pump diode array that resulted in excessive power degradation and catastrophic failure. Manufacturing of the laser diode arrays introduced excessive indium solder that resulted in a metallurgical reaction that progressively eroded the gold conductors through the formation of a non-conducting gold-indium intermetallic, gold indide, at a rate dependent on temperature.

The IGARB also concluded that it was likely that the same problem that affected Laser 1 also exists in Lasers 2 and 3. However, it is impossible to predict with certainty the performance of Lasers 2 and 3 since it is not possible to determine the exact condition of their diode arrays. Laser 1 had operated for approximately 74 days of pre-launch operations plus 36 days of on-orbit operations. Lasers 2 & 3 pre-launch operations were 44 & 37 days, respectively.

Based on these findings, the IGARB recommended that:

- 1) science operations be structured with the expectation of substantially reduced life from Lasers 2 and 3, and that Laser 2 be activated first with science operations structured with the expectation of substantially reduced life from Lasers 2 and 3, and that Laser 2 be activated first with on-orbit spacecraft and instrument operations structured to minimize the thermal stresses to which the laser diodes are subjected.
- 2) To reduce temperature-related effects of any indium contamination, the IGARB has recommended that Lasers 2 and 3 be operated at a 25°C reference temperature rather than the 29°C initially used for Laser 1.
- 3) use existing operations plans regarding turn-off as they apply to laser operations, but revise the survival mode recovery procedures to control the rate of

warm-up prior to turn-on to minimize thermal stresses and strains in the diode array solders.

These recommendations would have a dramatic impact on operations and thermal control over the remaining mission. However, before science operations could be resumed, an unexpected anomaly occurred with the Component LHP that provides thermal control to all non-laser avionics onboard GLAS.

THERMAL ANOMALY

On August 17th, just a few days before the scheduled resumption of the science mission with the activation of Laser 2, the GLAS CLHP “deprimed”, which caused an thermal runaway condition (Figure 11). Real-time discussions of the telemetry with the flight controllers at the Laboratory for Astrophysical and Space Physics (LASP) in Boulder, CO suggested a “slow flow” condition. An immediate attempt was made to prevent interruption to laser turn-on plans by using the LHP starter heater to re-establish flow; this did not work as envisioned and ended with an over-temperature shutdown of the GLAS instrument.

The initial thought was that the heater control thermistor had debonded or the controller malfunctioned causing a constant application of control heater power to the compensation chamber, which would stop the LHP and result in the over-temperature condition. However, housekeeping telemetry showed that the heater current went to zero when the temperature rose above the setpoint. As the GSFC engineering team reviewed telemetry, temperatures cooled until the survival heater circuits activated (Figure 12) which immediately stopped the LHP. This was also atypical behavior for this LHP and indicated lack of fluid available in the evaporator.

Initial thoughts as to the possible causes for the deprime included:

- 1) losing charge due to a slow leak (versus rupture of the LHP vapor or liquid lines)
- 2) mechanical damage to knife edge, secondary wick, or primary wick within the evaporator
- 3) large NCG or vapor bubble with secondary/primary wick deprime that resulted in vapor penetration into the core
- 4) particles (from machining operations on the sintered metal wick) clogging secondary/primary wick

The engineering team agreed that possibilities 1, 2, and 4 presented a major challenge to continue operations. However, if a build-up of NCG or vapor in the evaporator core was the problem, the team concluded that it might be possible to collapse or even flush the bubble by using the operational heater or survival heater (both located on the CC) to “push” cold liquid into the core. While either of

these heaters should accomplish this, the procedure for doing so differed drastically:

- 1) use of the operational heater required the EBOX to be powered ON; it represented an 85W heat load that is normally removed by the now non-operational CLHP, so timing of the commands and intermittent contact periods would be critical.
- 2) Using the survival heater to provide CC control necessitated the starter heater (60W) to provide heat load into the evaporator.

A review of the telemetry in the preceding days revealed that relatively minor temperature excursions, or "blips", preceded the main anomaly (Figure 8), which further supported the NCG or vapor bubble possibility.

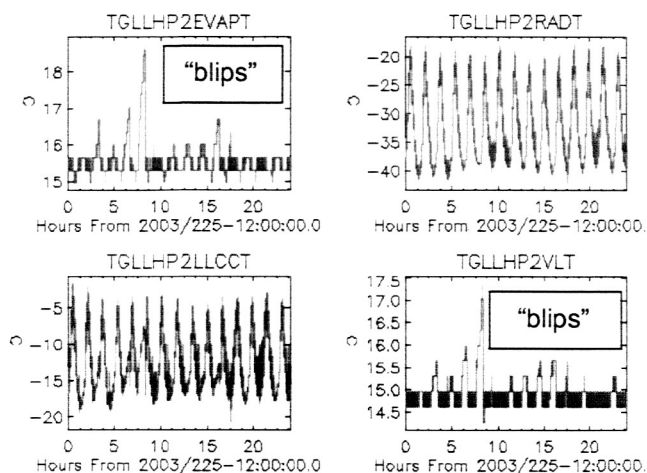


Figure 8 – Component LHP (LHP2) Precursors

Figure 13 and Figure 14 provide more detailed views of these "precursors". Figure 14 reveals that as the evaporator begins to warm near the coldest portion of the orbit, temperature oscillations in the liquid line dampen out, indicating reduced return flow of liquid from the radiator.

Figure 15 illustrates attempts using both approaches; the first (on Day 232; August 20th), was not successful although the LHP started and appeared to run for about 10 minutes, but then repeated the slow circulation and exhibited the same runaway condition as the original anomaly a few days earlier. However, the EBOX was turned OFF well before the high temperatures were reached. Afterwards, the CLHP again cooled until the survival heater activated which stopped the flow immediately (again, atypical). This time, the starter heater was activated and flow was re-established with the survival heater thermostat providing coarse temperature control to $-8^{\circ}\text{C} < T < -3^{\circ}\text{C}$. The CLHP remained in this configuration for several days until it was believed that any remaining NCG or vapor would have been flushed out of the evaporator or re-dissolved into the fluid.

A comparison of two similar operational conditions (Figure 18 and Figure 19) reveals visual differences in the LHP2 behavior; however, it continues to meet performance requirements.

GETTING BACK TO SCIENCE

Although the pre-launch operational plan included normal and contingency operations, a significant amount of support has been needed for non-planned events. Table 1 summarizes some of the significant thermal events for GLAS since launch.

Table 1 - GLAS Significant Thermal Events

Date	GLAS Event
Jan 12, 2003	Launch from VAFB
Feb 01, 2003	Component LHP start-up
Feb 08, 2003	Laser LHP start-up
Feb 20, 2003	Laser 1 firing
Mar 29, 2003	Laser 1 failure
May 09, 2003	ICESat S/A rotation stopped; Sun Acq (SAFE) mode, payload OFF; CLHP SU heater maintains flow
May 12, 2003	GLAS restart
Aug 17, 2003	CLHP deprime; GLAS emergency shutdown
Sep 25, 2003	Laser 2 firing
Oct 13, 2003	Wrong setpoint sent to Laser LHP via incorrect table load.
Nov 18, 2003	SCC reset; GLAS powered OFF 2 days before planned Laser 2 shutdown
Feb 17, 2004	Restart Laser 2
Feb 19, 2004	ICESat into Sun Acq: GLAS still operates due to changed limits.
Mar 21, 2004	Laser 2 OFF
May 20, 2004	Laser 2 firing (planned)
June 30, 2004	Laser 2 OFF (planned)

Now that the CLHP operation had been restored, the GLAS avionics and LLHP were activated in preparation for science operations using Laser 2, which was initiated on September 25th. After performing as expected, in consideration of the IGARB recommendations, planning

was for Laser 2 to be deactivated on November 20th and to be re-activated in the spring of 2004 in order to meet science goals for assessing temporal changes in altimetry and lidar science data. This plan was implemented earlier than expected when a reset of the spacecraft computer once again shut down power to the GLAS instrument. The ICESat project decided to resume GLAS operations, except for the lasers, waiting until the following February (winter season peak in northern hemisphere) to reactivate Laser 2 and again in May to obtain data during the Greenland snow melt season.

Laser 2 reactivation was successful on February 17th, 2004 and science operations continued until March 21st with only a minor interruption caused when the spacecraft went into Sun Acquisition mode at on February 19th. After a similar event on May 3rd, 2003, the payload was not automatically turned off when entering this mode. This event resulted in only a minor loss of science data for about 9 hours on the altimeter and 14 hours on the SPCMs. The evaporator temperature (TGLLHP2EVAPT) variations seen in Figure 17(a) result from the thermistor being in close proximity to the starter heater and voltage variations caused by eclipses appear to cause significant temperature variations. A better indicator of the temperature stability is the vapor line temperature (TGLLHP2VLT) in Figure 17(d).

CONCLUSIONS

A comparison of the thermal data from 2 weeks prior to the initial anomaly to similar conditions earlier in the mission, illustrates some visual differences in performance characteristics of that LHP, yet it continues to operate and meet thermal control requirements. This anomaly, coupled with the failure of the first laser, has constrained mission operations and, since restoring LHP operations, Laser 2 has been used under even more extreme thermal control requirements that were prescribed by the Laser 1 failure investigation.

While conclusive evidence has not been determined as to a particular reason for deprime of the GLAS Component LHP, science operations have been restored within the limitations of the lasers. It is believed that NCG (or vapor) ingested into the evaporator core "blocked" the fluid from the wick and led to dryout. NCG could have been present throughout the system when the combination of jitter from the SC yaw maneuver combined with the cooling of the radiator (condenser) due to the yaw maneuver resulted in sufficient vapor and/or NCG to be ingested into the evaporator causing the deprime. The recovery method of using the survival heater to "pulse" cold liquid and flush the evaporator supports this theory. However, at this time, a gradual loss of fluid due to a slow leak would exhibit similar characteristics and should not be ruled out. Continued operation of the CLHP will be closely monitored for performance deterioration that would be evidence of such a leak.

ACKNOWLEDGEMENTS

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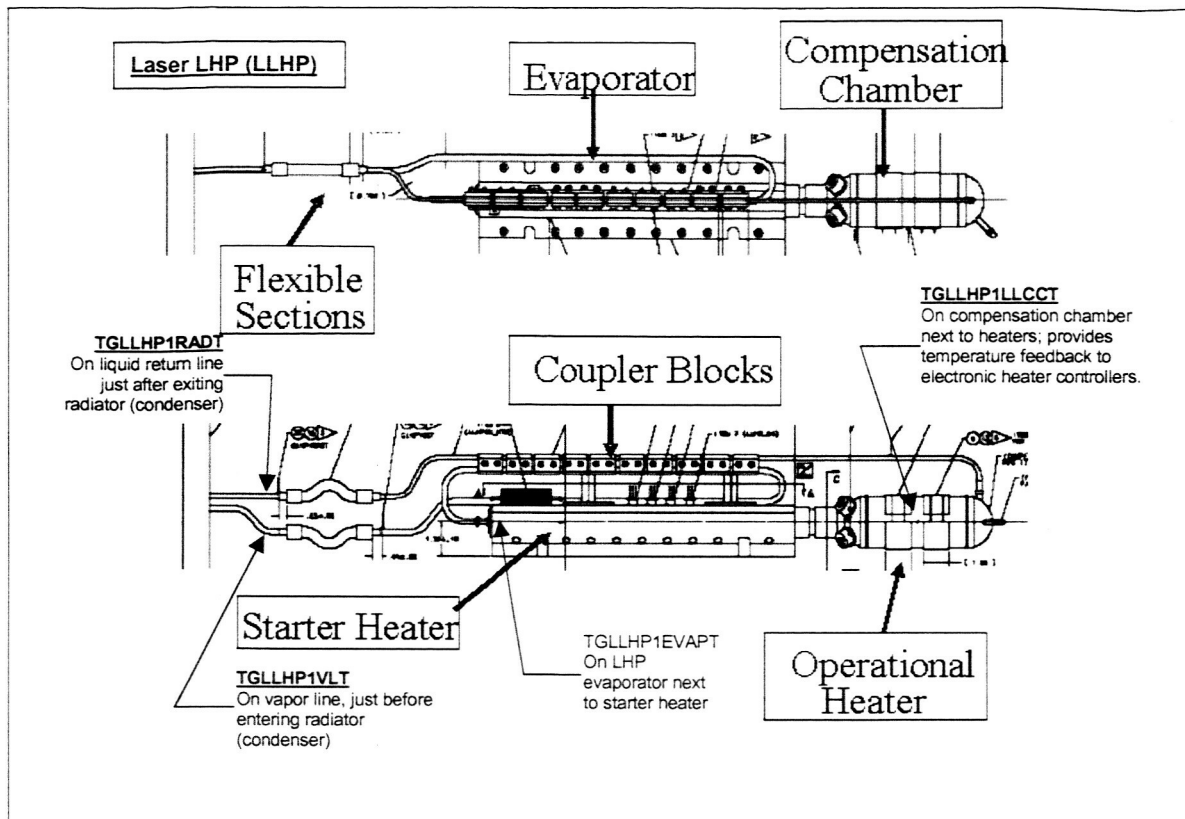


Figure 9 – GLAS LLHP Telemetry Locations

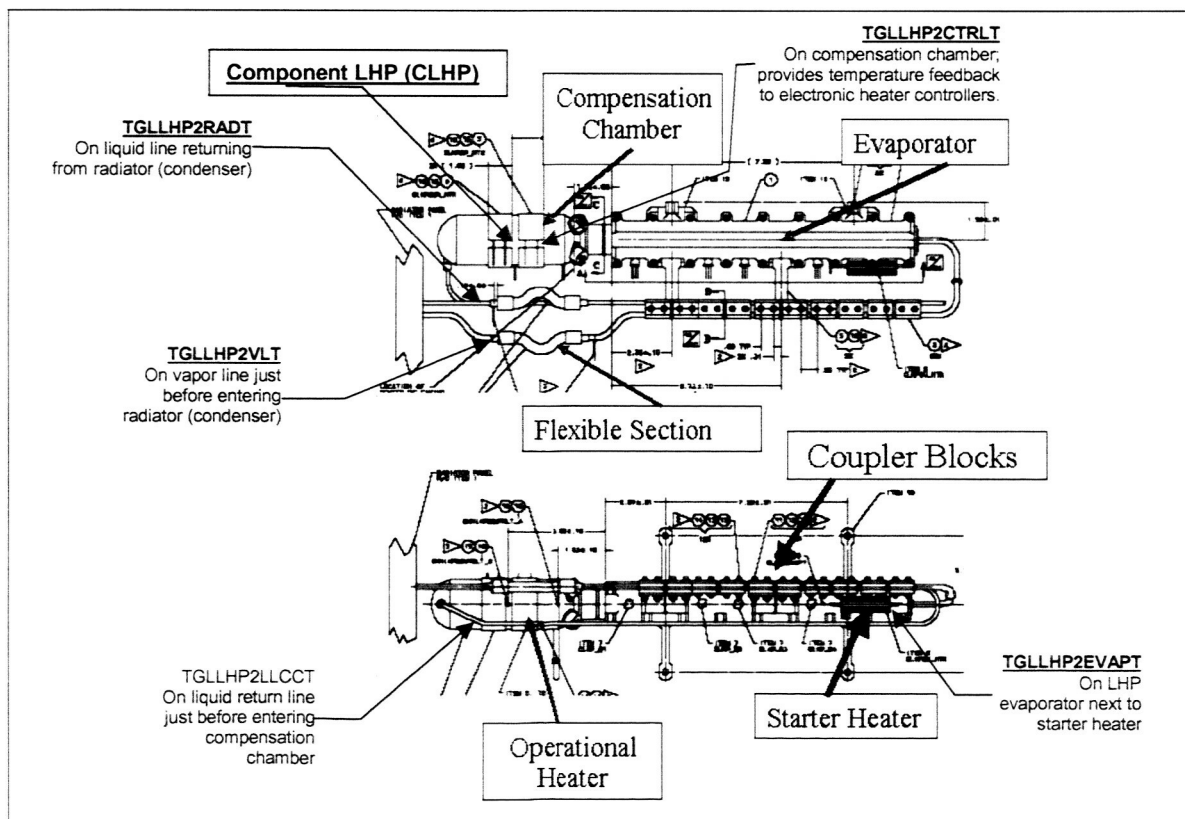


Figure 10 – GLAS CLHP Telemetry Locations

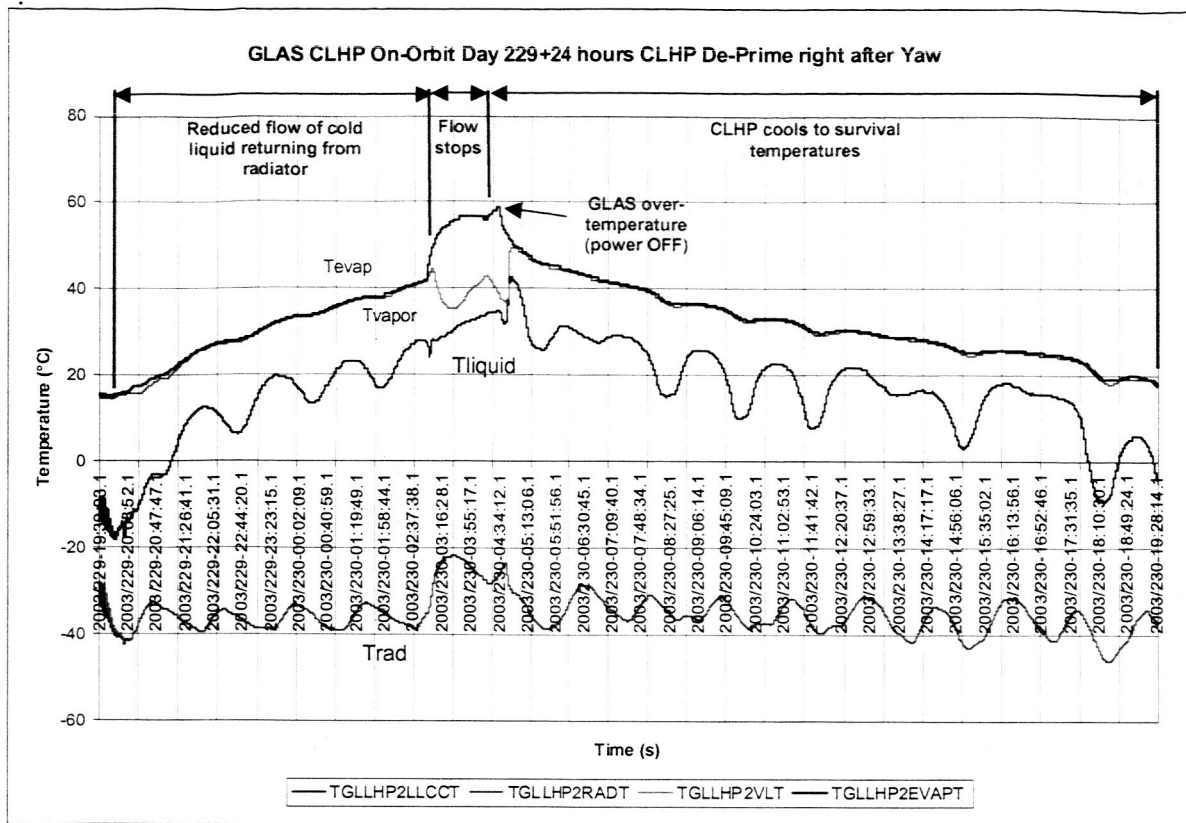


Figure 11 – GLAS Component LHP Anomaly

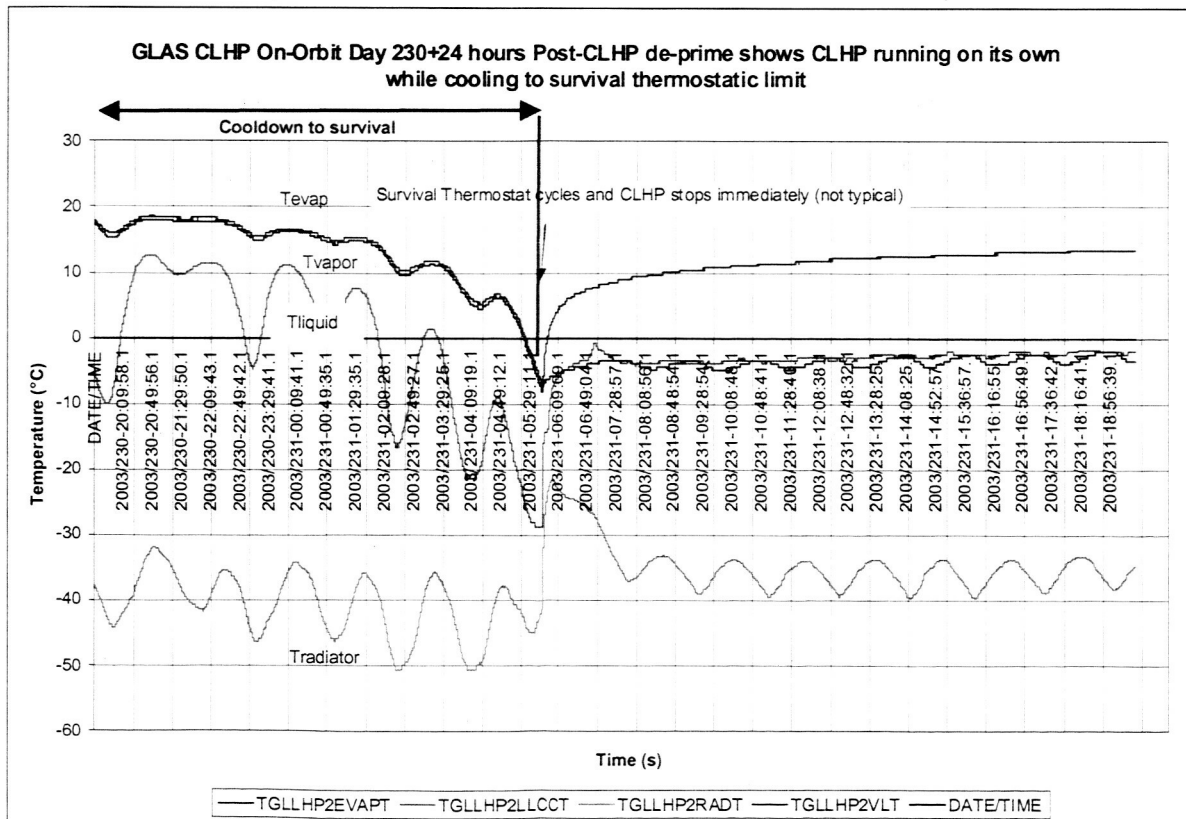


Figure 12 – Cooldown to Survival

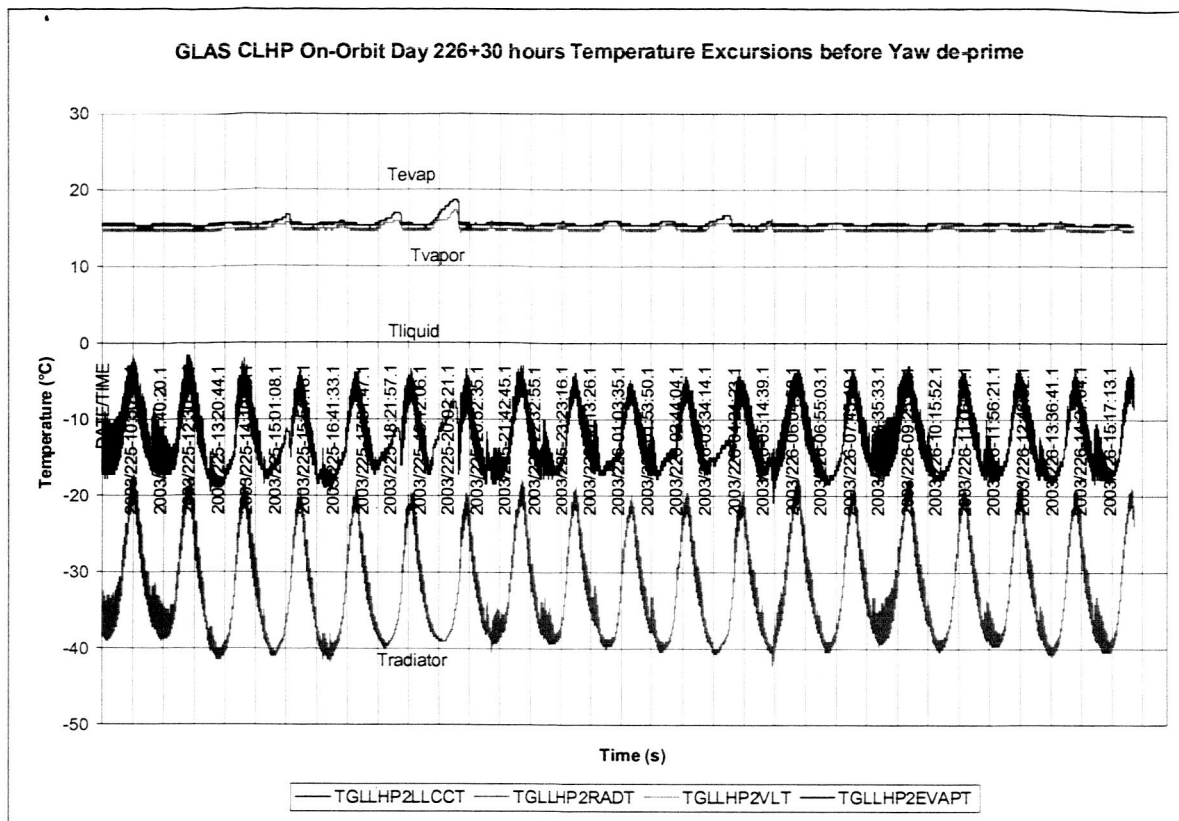


Figure 13 – Precursors to the Anomaly

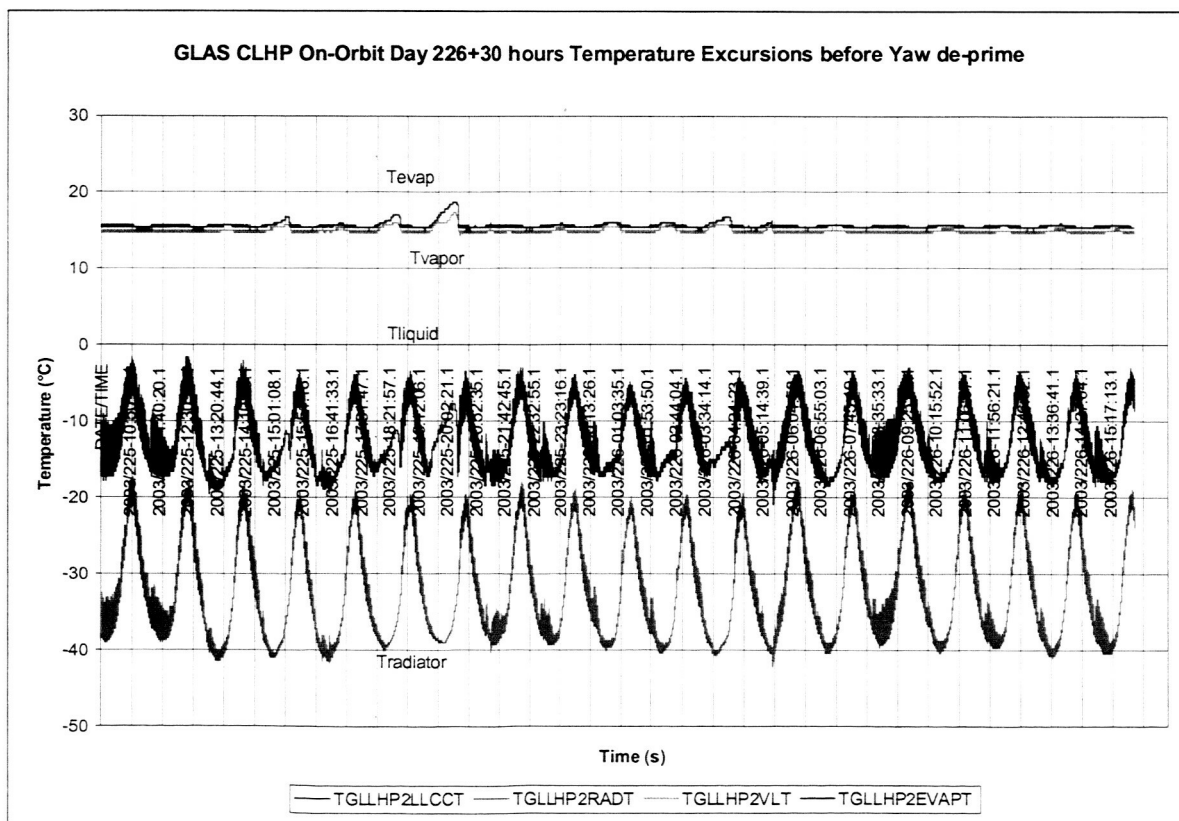


Figure 14 – Detailed View of the Precursors

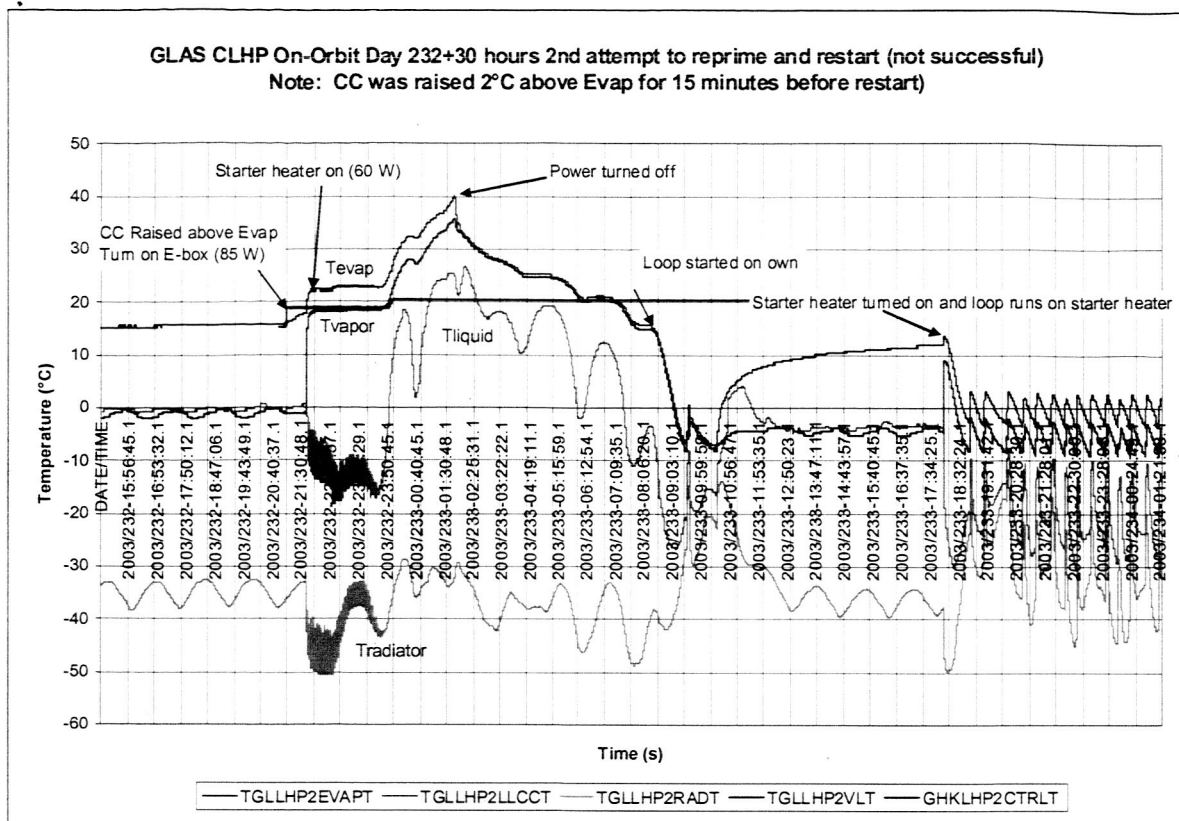


Figure 15 – Restarting the CLHP

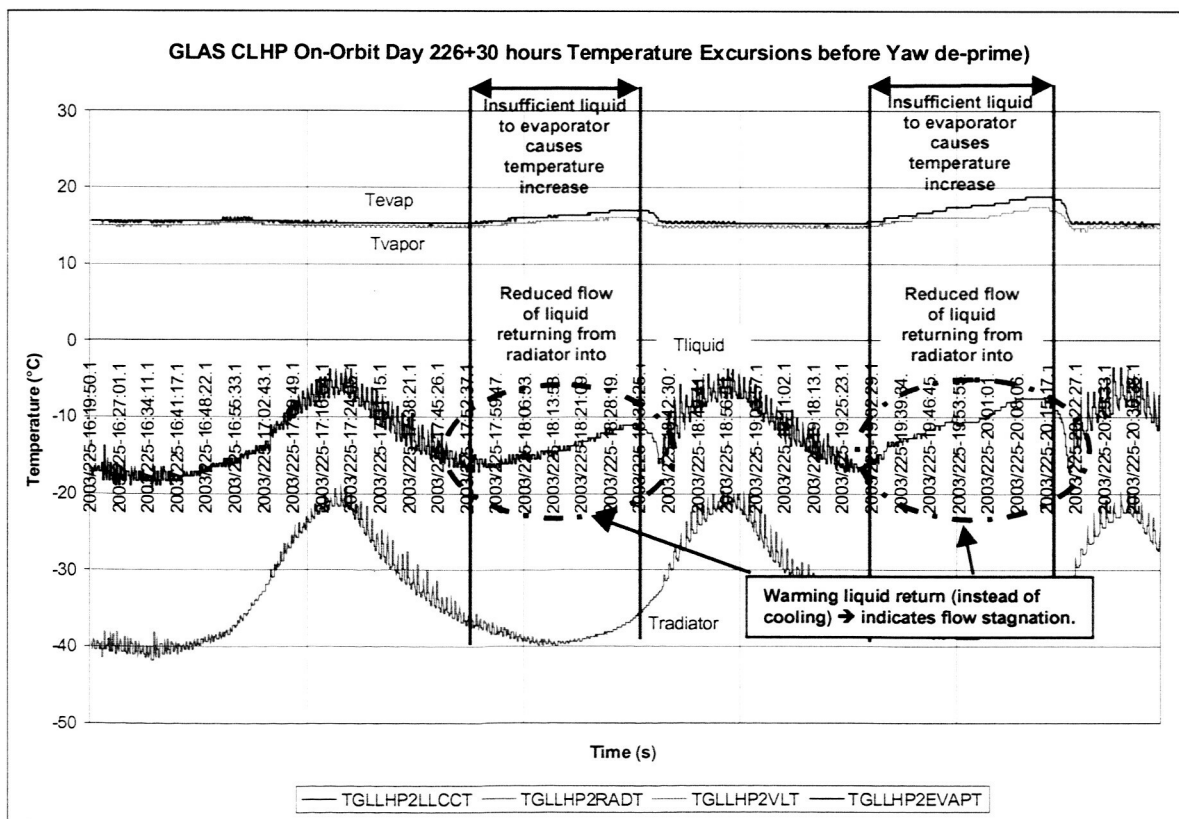


Figure 16 – Precursors to the Anomaly

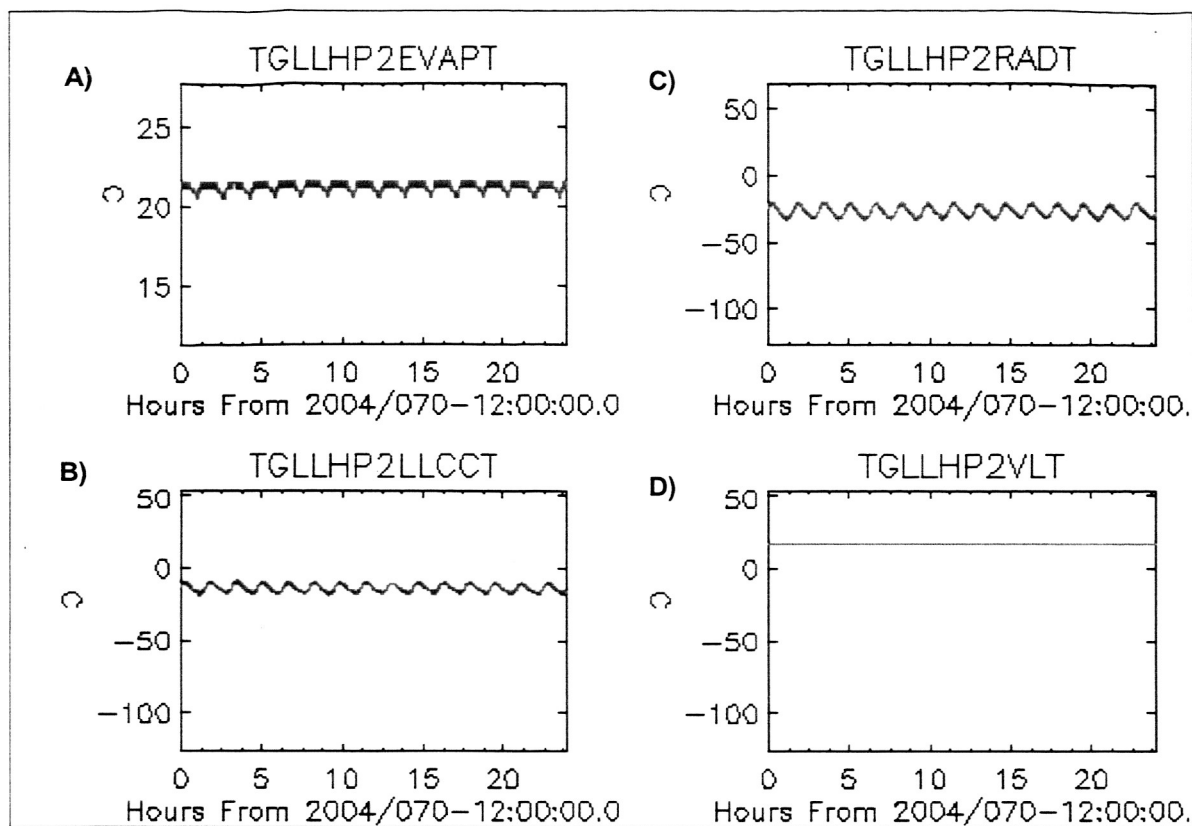


Figure 17 – Current CLHP Temperature Telemetry

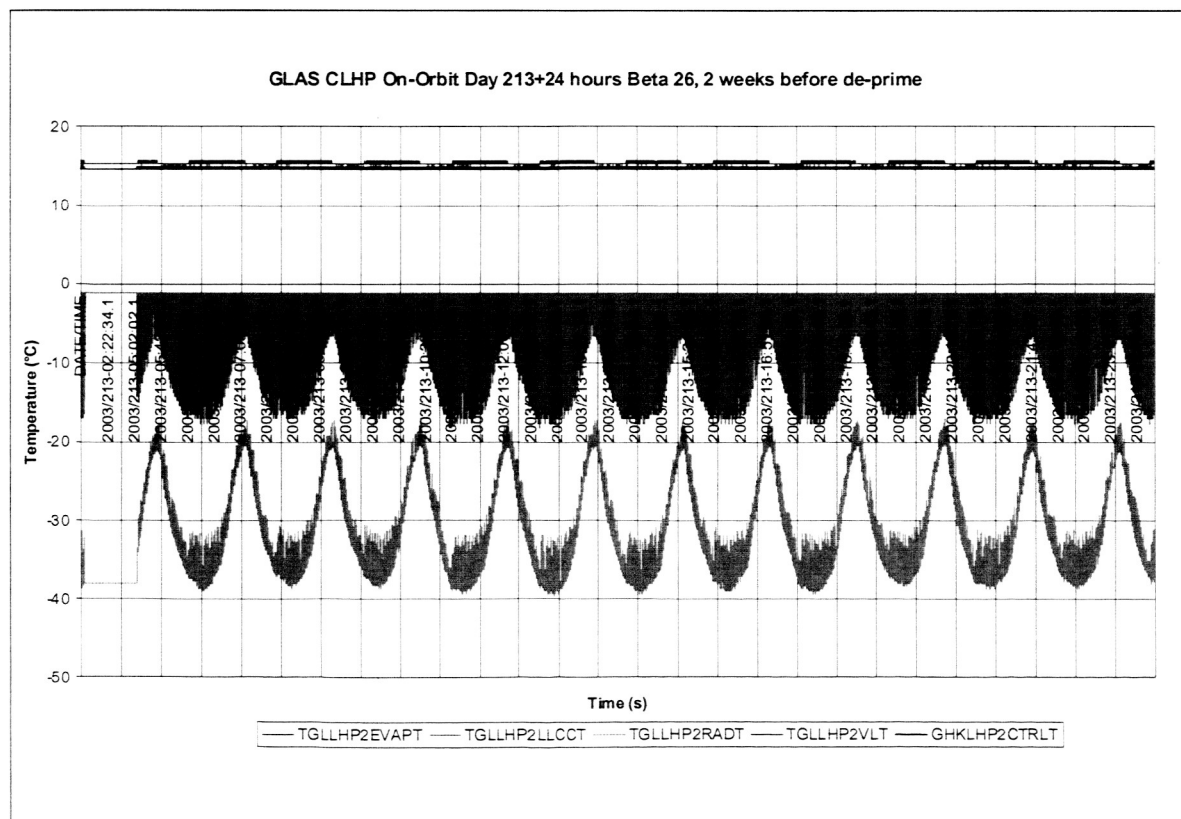


Figure 18 – CLHP Telemetry from Day 213 (Aug 1, 2003) Prior to Anomaly

